

# A Dual Production Analysis of a Multispecies Fishery: The Case of the U.S. Atlantic Longline Fleet

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**Abstract.** The harvest technology of several multispecies fisheries has been explained in the recent literature using dual-based models. These studies are useful for explaining rent dissipation, estimating input and output elasticities, as well as describing other aspects of fisherman behavior. Most of these analyses have assumed that inputs are fixed at the trip level. Consequently researchers have argued that firms participating in multiple fisheries behave as revenue-maximizers. This paper describes an empirical model of a multispecies fishery that assumes decision-makers are cost-minimizers at the trip level. A theoretical argument justifying this assumption is presented. Using duality theory, optimal input demands are estimated using data from the U.S. Atlantic pelagic longline fleet using iterative seemingly unrelated regression (SUR) and a recently suggested approach. These results are used to describe the economic characteristics of the industry and the economic consequences of proposed regulations, with focus on the demand for fuel. Additionally, an EM (Expectation-Maximization) algorithm is employed to correct for missing data problems. The efficiency of the algorithm is explored by rerunning the original analysis using the newly created data set and comparing results.

**Keywords.** duality, longline, production economics, swordfish

## 1. INTRODUCTION

The lack of enforceable property rights to fish can lead to inefficient allocations of rents in single and multispecies fisheries (Gordon, 1954). Regulators attempt to generate (possibly by diversion from other stakeholders) societal rents through restrictions that curtail the “open-access” nature of the fishery. Examples of these regulations include input controls, catch quotas, time-area closures, and license/vessel buyback programs. Fisheries that are multispecies or multicohort present a multidimensional challenge to fishery managers (Squires and Kirkley, 1995). One such fishery, the Atlantic and Gulf of Mexico highly migratory species (HMS), and the fleet that targets it are the focus of this paper.

Over a decade has passed since the Fishery Conservation Amendments of 1990 consolidated management of the HMS in the U.S. exclusive economic zones of the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea under the authority of the Secretary of Commerce; yet, current and pending legislation does not fully incorporate the economic linkages between these species. The economic relationships arise in large part due to the non-discriminatory nature of longline gear, which is the dominant method of harvesting Atlantic HMS. The midwater longline is “a continuous mainline suspended in the water by a series of floats with regularly spaced leaders attached that end with baited hooks” (Atlantic States Marine Fisheries Commission, 1997, p.32) causing indiscriminate harvests of not only targeted and non-targeted HMS but also commercially worthless species such as undersized juvenile HMS, marlin, birds, and other marine animals. Recently, HMS managers have designated overfished stocks of Atlantic and Gulf HMS and excess fishing mortality caused by bycatch and discards due to longlines as two primary problems for resolution.

The U.S. Atlantic pelagic longline (PLL) fleet fishes out of harbors from Maine to Florida and from Texas to the Caribbean, comprises as many as 354 vessels ranging in size from 34 to 85 feet, and specifically targets HMS. In 1996, the fleet landed nearly 240,000 fish and sharks valued at \$42 million dockside. Landings included swordfish, BAYS tunas (bigeye, albacore, yellowfin, and skipjack), dolphin fish (mahi-mahi), and pelagic and large coastal sharks (i.e., makos, porbeagles, threshers, sandbars, silkys, blacktips, duskys, and hammerheads). Extensive statistical information on the 1996 PLL fleet is presented in Larkin, Adams, and Lee (2001).

Management of Atlantic HMS is delegated from the Secretary of Commerce to the National Marine Fisheries Service (NMFS). NMFS has identified several of the HMS species targeted by longliners as being “overfished”: west Atlantic bluefin tuna, Atlantic bigeye tuna, north Atlantic albacore, north Atlantic swordfish, and large coastal sharks. Currently, Atlantic and Gulf HMS are jointly managed by NMFS under the 1999 Fishery Management Plan (FMP) for Atlantic Tunas, Swordfish and Sharks. By attempting to manage these species under a single plan, regulators acknowledge the importance of biological and economic interactions among the

HMS species. However, current and proposed time-area closures for individual species do not fully account for the multispecies nature of the fishery; this may lead vessels to adjust their input mix such that unregulated species are targeted more heavily, and industry production is inefficient.

Management goals for U.S. fish stocks in general are to conserve the biological resource and to achieve economic efficiency within the fishery. In doing so, the transition costs and economic displacement to the industry and fishery communities must be minimized according to the Magnuson-Stevens Fishery Conservation and Management Act (NMFS, 1999). If future HMS policies and regulations are to be efficient, cost information from the longline industry must be duly considered.

The need for more detailed and realistic economic information is highlighted by recently enacted regulations that affect specific fishing areas and components of the fleet. For example, since March 2001, 133,000 square miles of U.S. waters in the south Atlantic and Gulf of Mexico have been closed partially or entirely to longline fishing to protect juvenile swordfish populations. The enactment of time-area closures, and proposal of set quotas, suggests that resource managers are still willing to micromanage the fleet without considering the system-wide effects of the regulations (i.e., effects on all fisheries and fishing communities). If system-wide effects exist, then imposing blanket regulations on a heterogeneous fleet with nondiscriminatory gear may not be efficient or effective.

Enactment of time-area closures restricts the amount of rent generation by fishermen to zero during the regulation period while society accrues benefits in the form of rejuvenated fish stocks. Although fishermen may also benefit in the future from higher catch rates, the Magnuson-Stevens Act requires regulators to examine the immediate economic impact of the closures on Atlantic longliners. In this light, managers might consider the effects of trip-level input controls. Generally, input controls are considered to be an inefficient regulatory tool when trying to allocate rents in a fishery (Dupont 1990). However, in some situations, net benefits still accrue after input restrictions, which raises the possibility that input controls might be a more equitable policy (Anderson, 1985). In the case of longliners, trip-level input controls allow fishermen to derive some present economic benefit from previously closed grounds while still allowing for stock regeneration and future benefit flows to society.

This paper describes an empirical model of the pelagic longline fleet (the predominate gear type used in to harvest HMS fisheries in the Atlantic, Caribbean, and Gulf of Mexico) that can be used to evaluate allocative and distributional economic effects to the industry of proposed changes in HMS regulations. The estimation approach and results build on and differ from that found in Larkin et al. (in press). The methods presented in this paper have value to fishery managers worldwide trying to accurately measure and capture rents from open-access multispecies fisheries, especially where fishermen face stochastic harvest levels.

## **2. MODELING THE PLL FLEET FROM THE COST SIDE**

An analysis of the fleet's harvesting technology provides valuable information to managers assessing the effects of input or output directed regulations. A number of studies in fisheries management have utilized duality theory to explain commercial harvest technologies and investigate policy implications within both single and multiple species fisheries. The methodologies are diverse yet share the same crucial first step. Based on industry and operator characteristics, the researcher must initially specify an objective function. A misspecified model, due to incorrect assumptions may cause results to be biased or inconsistent resulting in misguided policy decisions.

Many analyses (Kirkley and Strand, 1988; Squires and Kirkley, 1991; Thunberg, Bresnayan, and Adams, 1995; Squires and Kirkley, 1996) have relied on the assumption that inputs are sufficiently specified with a single measure (typically a function of vessel capacity or some other set capital attribute) that is fixed during a trip. This assumption has allowed researchers to argue that firms participating in multiple fisheries attempt to maximize revenue subject to a single quasi-fixed input instead of maximizing profits directly. When assuming constant input prices and a fixed input portfolio, maximization of the profit function is equivalent to a revenue maximization problem. Thus, a majority of the literature has focused on optimal harvest strategies while secondary attention has been paid to input mixes and factor prices.

However, some studies invoke the stronger behavioral assumption of profit maximization. Squires (1987b) specifies a translog functional form for a multiproduct profit function to estimate the harvest technology for the New England otter trawl fleet. Dupont (1990) specifies a normalized quadratic restricted profit function to ultimately generate measures of rent dissipation in the British Columbia commercial salmon fishery. Although

dual profit specifications yield extensive information on harvest technologies, industry characteristics and data limitations sometimes preclude their application in multispecies fisheries such as for highly migratory species.

Following Mistiaen and Strand (2000), the PLL fleet are effectively price takers in both input and output markets and face stochastic harvests. In this situation, duality theory tells us that the profit maximization problem reduces to an optimal variable input mix decision that minimizes costs; thus, at the trip level, PLL vessels operating in Atlantic, Caribbean, and Gulf of Mexico waters are assumed to be cost minimizers.

Few articles have modeled fishermen as cost minimizers. Pascoe and Robinson (1998) solve the cost minimization problem for a translog production function representing the technology of vessels participating in the multispecies beam trawl fishery in the English Channel. They found that input controls caused vessel owners to make inefficient input substitution decisions by trading engine power for access to restricted fishing grounds. The PLL fleet in this study faces a similar dilemma when time-area closures force captains to use valuable inputs to travel to open fishing grounds.

Jensen (2002) reports that three studies have utilized a dual cost framework in fishery economics to describe vessels operating under output regulation. Lipton and Strand (1992) estimated multiproduct quadratic cost functions to explain the technology of the Atlantic clam fishery. They used this information to perform simulations that showed an increase in the number of participating vessels, a decrease in clam catch per vessel, and an increase in ocean quahog harvest would be optimal. Weninger (1998) estimated a translog cost function that also depicted the technology of the Mid-Atlantic surf clam and ocean quahog fishery. The study also presented a general methodology to assess the efficiency gains from an individual transferable quota (ITQ) management regime. Lastly, Bjørndal and Gordon (2000) estimated a translog cost function to explain the economic structure of the technology in the Norwegian spring-spawning herring fishery. They reported input elasticities, economies of scale, and cost elasticities. An additional study not mentioned by Jensen that also models commercial fishers as cost-minimizers using the dual framework is Dupont (2000). Dupont estimated a normalized quadratic restricted cost function for four gear types in the British Columbia salmon fishery to generate measures necessary for a subsequent simulation of a market for ITQs.

Using the cost-minimization approach, the PLL vessel captain is assumed to use variable inputs,  $X_1, \dots, X_K$ , and a fixed capital input  $Z$ , in a way that minimizes harvesting costs for a random catch,  $Y_1, \dots, Y_M$ , where  $X$  is a  $K \times 1$  vector of input quantities,  $R$  is a  $K \times 1$  vector of variable input prices, and  $Y$  is a  $M \times 1$  vector of landings for each HMS species. The fleet is assumed to be a price taker in both input and output markets. Thus, the vessel captain chooses a variable input mix in an effort to minimize trip-level harvest costs. This implies that captains choose a level of effort – based on an expected, stochastic catch distribution (Zellner, Kmenta, and Dreze, 1966) – to minimize variable costs. Consequently, in this study once a targeting strategy is specified, the PLL vessels are assumed to be able to only make variable input mix decisions that minimize trip costs and maximize trip profits.

For each trip a dual flexible cost function is specified by equation (1) in outputs, factor prices, and a fixed input while dummy variables ( $D$ ) are used to account for the location of the arrival port, trip length, and season. Note that  $q(X;Z)$  is the short-run harvest production function:

$$(1) \quad C(R; Z, Y, f(D)) = \min_X \{R^T X; q(X; Z) \geq Y\}.$$

Since prevailing knowledge about the fishery and fleet does not dictate a particular functional form, a normalized quadratic form is assumed for the empirical model following Dupont (2000). A normalized quadratic cost function for the Atlantic PLL fleet was defined and estimated in Larkin et al. (in press) as:

$$(2) \quad C(r, Y, Z, f(D)) = \alpha_o + \sum_{i=1}^3 \alpha_i r_i + \frac{1}{2} \sum_{i=1}^3 \sum_{j=1}^3 \alpha_{ij} r_i r_j + \sum_{k=1}^5 \beta_k Y_k + \frac{1}{2} \sum_{k=1}^5 \sum_{l=1}^5 \beta_{kl} Y_k Y_l + \sum_{i=1}^3 \sum_{k=1}^5 \gamma_{ki} r_i Y_k \\ + \mu Z + \omega Z^2 + \sum_{i=1}^3 \lambda_i r_i Z + \sum_{k=1}^5 \varsigma_k Y_k Z + \sum_{i=1}^3 \rho_{in}^m r_i D_n^m \Big|_{mn}$$

where  $r_i$  represents the prices of light sticks, bait and fuel (i.e., variable inputs) normalized by the price of ice.<sup>1</sup>  $C$  is trip-level variable cost, also normalized by the price of ice. The fixed trip-level capital constraint is assumed appropriately represented by vessel length ( $Z$ ). Using Shephard's lemma, the cost-minimizing demand functions are easily obtained (i.e.,  $\partial C(\cdot)/\partial r_i = x_i(\cdot)$ ).

### 3. ESTIMATION

The empirical model was specified with normalized input prices for light sticks, bait, and fuel. The output quantities ( $Y$ ) were grouped as follows: BAYS tunas, dolphin fish, shark, swordfish, and other fish. Output prices were derived from reported revenues and assumed fixed at the trip-level since individual trip-level prices were not collected. Furthermore, output levels are considered exogenous to the model since harvest levels are assumed to be stochastically determined. Three categories of dummy variables are included to account for observed heterogeneity within the PLL fleet and Atlantic HMS fisheries (Larkin, Adams, and Lee, 2001; Larkin et al., in press), namely: geographic region of arrival port ( $D^G$ ), quarter ( $D^Q$ ), and trip length ( $D^L$ ). The geographic regions are the Caribbean, Gulf of Mexico, Northeast (base region), and the Mid-Atlantic or southeast. The seasons (quarters) are January-March (base quarter), April-June, July-September, and October-December. Trip lengths based on number of sets are grouped as follows: 1-3 sets, 4-6 sets, 7-9 sets, or 10-21 sets (base category). Trip length approximated by the number of sets per trip is also a measure of fishing effort expended at the trip level. The input demand equations for light sticks ( $i=1$ ), bait ( $i=2$ ), and fuel ( $i=3$ ) are given by:

$$(3) \quad x_i(r, Y, Z, f(D)) = \alpha_i + \sum_{j=1}^3 \alpha_{ij} r_j + \sum_{k=1}^5 \gamma_{ik} Y_k + \tau_i Z + \rho_{in}^m D_n^m |_{mn}$$

In summary, the average trip used 1,317 light sticks, 1,831 pounds of bait, and 1,825 gallons of fuel; however, relatively large standard deviations indicated significant heterogeneity (Larkin et al., in press). Output per trip displayed even further heterogeneity. Landings of swordfish, BAYS tunas, sharks, and dolphin averaged less than 30 fish per trip. The majority of trips departed from the Gulf of Mexico region (48%), which spans from Key West Florida to Texas. Trips in the sample data were dispersed throughout the year. In terms of trip length, as represented by the number of sets, the sample was evenly divided with the exception of the longest trips; only 16% of trips placed at least 10 sets. For additional statistics, interested readers are referred to Table 2 in Larkin et al. (in press).

The system of three normalized input demand functions were estimated using iterative seemingly unrelated regression (SUR) in order to account for the possible correlation of error terms across equations in the system. The following analysis amends a previous study, Larkin et al. (in press), that did not account for possible variable endogeneity.

The trip-level economic data (primarily cost information) on this fishery was collected under a voluntary program initiated in 1996. Complete data was received on nearly 20 percent of trips and reported by 47 percent of the fleet, 552 trips in total, which covered all the heterogeneity observed within the PLL fleet as noted in Larkin, Adams, and Lee (2001). Incomplete observations (on the remaining 2,088 trips) lacked responses in regards to input usage yet included trip-level information on landings, vessel length, port of origin, number of sets, and seasonality. The preceding dual analysis assumes that the information is "missing completely at random"; thus, deletion of incomplete observations leads to unbiased and consistent regression estimates using a simple random subsample from the original set of observations (Allison, 2002). However, missing economic information may be a nontrivial concern since it could introduce non-response bias, possibly render the sample too small for meaningful statistical analysis, and distort policy inferences.

To address this issue we propose an algorithm for computing maximum likelihood (ML) estimates from incomplete data. We apply this algorithm (i.e., the Expectation-Maximization, EM, algorithm) to data from this fishery in an attempt to extract additional information from the incomplete observations (Dempster et al., 1977). To our knowledge, this is the first application of the EM algorithm to commercial fisheries, and in light of the chronic problem of missing data associated with empirical fishery studies, the methodology appears promising. Regression results that use the EM algorithm are true ML estimates and are close to the results obtained by deleting incomplete observations.

<sup>1</sup> Dupont (2000) notes that previous research shows parameter estimates are robust with respect to choice of the normalizing variable.

The ML estimator of  $\theta$ , a vector of parameters, is the vector that maximizes the log-likelihood function of the observed data (i.e.,  $\theta'$ ). Initially, an estimate of  $\theta'$  is generated by maximizing  $\ln L = \sum_i \ln f(y_i | \theta, x_i)$  where  $y_i$  are the observed values,  $f(\cdot)$  is the density function for  $y_i$  and  $x_i$  is data that enters the distribution. The EM algorithm proceeds in two steps:

(4a) E step: Form  $H(\theta'_1, Y, X) = E[\sum_i \ln f(y_i^* | \theta, y_i, x_i)]$

(4b) M step: Maximize  $H(\cdot)$  to obtain  $\theta'_{1+1}$

The E step involves forming a log-likelihood function for the latent data as if they were observed, then taking its expectation. This generates a “synthetic”  $y_i^*$ , equal to  $H(\cdot)$ , based on the initial estimate  $\theta'_1$ . When normality is assumed, this is the same as forming a prediction of  $y_i^*$  and then using  $y_i^*$  to maximize the likelihood function. The M step uses the ordinary least squares (OLS) estimation procedure to obtain predictions of  $\theta'_{1+1}$  on  $X$ . Once this estimate is obtained it is substituted back into the E step and the algorithm starts a new iteration. Under these conditions the algorithm converges to ML estimates and the generated synthetic  $y_i^*$  are ML estimates of the missing data. Since the majority of parameter estimates associated with fuel demand are not significant, we applied the EM algorithm to this input demand equation.

#### 4. RESULTS

All results pertain to the demands for the three inputs estimated, namely: light sticks, bait, and fuel. The estimated constant intercept parameters reflect, in part, the input demands associated with the “base” trip which is one that concluded at a northeast port (i.e., from Maine to Virginia) between January and March and had fished 10 to 21 sets in 1996. Estimation results for the fuel equations are summarized in Table 1. The first column of results represents the parameter estimates and corresponding standard deviations associated with the initial SUR analysis using Zellner’s iterative procedure. The second column represents least squares estimation only on the optimal fuel demand equation. The third column employs the EM algorithm and utilizes the complete data set of 2,640 observations.

Prices and demands were inversely correlated indicating that all inputs are “normal”. Some input relationships were found to be complementary, for example, an increase in the price of bait decreased the demand for light sticks. An increase in BAYS tunas was found to decrease the use of lightsticks and an increase in the harvest of swordfish was found to increase the use of light sticks, which make sense since the lightsticks are used to attract swordfish. From the SUR results, the estimated input price effects reveal that bait and lightsticks are compliments and normal goods. Fuel price was not found to have a statistically significant affect on input decisions. The vessel length effects ( $Z$ ) were statistically significant for the demand of each input. Regarding input and output relationships, swordfish and BAYS tuna landings had a statistically significant effect on the demand of all inputs. The dummy variable effects indicated that the demand for lightsticks was highest in the Caribbean region and for longer trips. Bait and fuel demand was highest in winter, in the Caribbean region, and for longer trips. Regarding the own-price elasticities, they were negative and less than one for bait and lightsticks across all dummy variable categories.

Overall, the reported standard errors are much lower suggesting that the EM algorithm did not produce ML estimates of the covariance matrix. In fact, this is a major drawback to the EM algorithm and will be the major focus of future work since accurate managerial decisions rely heavily on the significance of particular parameter estimates.

**Table 1. Input Demand for Fuel by Estimation Method (Estimated Parameter Values for Equation 3,  $i=3$ )**

<i>Variable</i>	<i>Iterative SUR</i> ( <i>n</i> = 552)	<b>OLS</b> ( <i>n</i> = 552)	<i>EM</i> ( <i>n</i> = 2,640)
Constant <sup>a</sup>	-1,062.73** (448.09)	-934.20** (462.8)	-746.40*** (106.8)
Input Price Variables:			
Light Sticks ( $r_1$ )	-1.23 (5.82)	-10.84 (13.26)	-9.11* (4.82)
Bait ( $r_2$ )	-0.07 (4.47)	15.83** (8.04)	16.19*** (2.98)
Fuel ( $r_3$ )	-7.96 (6.72)	-16.21 (9.91)	-17.16*** (3.61)
Vessel Length ( $Z$ )	57.08*** (5.03)	55.12*** (5.37)	51.39*** (1.05)
Output Quantity Variables:			
Swordfish ( $Y_1$ )	21.65*** (1.49)	21.25*** (1.52)	21.14*** (0.26)
BAYS Tunas ( $Y_2$ )	7.13*** (1.54)	6.78*** (1.56)	6.86*** (0.31)
Dolphin Fish ( $Y_3$ )	1.44 (1.64)	9.53 (6.59)	4.84*** (0.35)
Sharks ( $Y_4$ )	3.48 (2.46)	4.00 (2.51)	2.99*** (0.15)
Other Fish ( $Y_5$ )	-13.70** (6.45)	-8.06 (6.23)	-4.02*** (0.52)
Dummy Variables <sup>a</sup>			
NC to Miami, FL ( $D^G_1$ )	-158.86 (197.70)	-200.40 (202.1)	-103.70*** (39.49)
TX to Key West, FL ( $D^G_2$ )	-221.78 (189.97)	-232.36 (195.9)	-233.20*** (39.26)
Caribbean ( $D^G_3$ )	448.64* (270.63)	369.73 (277.9)	377.50*** (64.39)
April - June ( $D^Q_1$ )	-111.04 (154.61)	-103.43 (157.5)	-85.97*** (32.52)
July - September ( $D^Q_2$ )	-108.02 (166.23)	-96.04 (169.5)	-97.46*** (33.58)
October - December ( $D^Q_3$ )	-140.58 (179.54)	-115.61 (183.8)	-113.80*** (39.20)
1-3 Sets ( $D^L_1$ )	-834.10*** (219.84)	-815.06*** (224.00)	-736.90*** (54.10)
4-6 Sets ( $D^L_2$ )	-673.41*** (194.41)	-679.28*** (197.99)	-691.93*** (45.99)
7-9 Sets ( $D^L_3$ )	-687.12*** (187.32)	-703.96*** (191.08)	-717.14*** (44.88)

Note: Single, double, and triple asterisks indicate statistical significance at the 10, 5, and 1% levels, respectively. Standard errors are in parentheses below the coefficients.

<sup>a</sup> The constant will reflect demand by trips with ports located from Maine to Virginia, departing in January, February, or March, and fishing from 10 to 21 sets.

## 5. CONCLUSIONS

Management of the Atlantic and Gulf HMS fishery is complicated due to the biological and economic interactions of many different species, a basically indiscriminate method of harvesting (i.e., longlining), and societal pressure to preserve the vitality of the biological stock for future benefits. Current regulations are indiscriminate in that they do not incorporate the potential substitution effects once vessel operators redirect

effort to unregulated species or areas in response to time-area closures. Since longline operators are assumed to only be able to control their input mix at the trip-level, managers may want to investigate trip-level input controls to achieve the desired level of stock regeneration while giving vessels the opportunity to derive some rents from fishing grounds targeted for closure.

This paper specifies a dual model of the PLL fleet's harvesting technology that has broad applicability to multispecies fisheries worldwide, especially where vessel operators face stochastic harvests and take output and input prices as given at the trip-level. The results give managers vital economic information about the likely reactions to regulations. In the case of time-area closures, the evidence seems to suggest that captains are very likely to trade extra fuel in search for open fishing grounds. Regulators should recognize the burden of inefficient production these closures place on operators: not only do they receive zero rents from their old fishing grounds; they also are forced to trade valuable fuel inputs for new fishing locations. Instead, regulators may want to examine the effect of trip-level taxes on fuel, light sticks, or bait to curb harvesting in certain regions. At least vessels would be able to make a marginal decision about whether to stay in the disputed area, use fuel inputs to search for new fishing grounds, or leave the industry.

Comparison of the results from the three estimations suggests that the EM algorithm performs robustly in regards to parameter estimation and, thus, the calculation of elasticities. All parameter estimates associated with EM estimation have the same sign as estimates associated with the SUR and OLS regressions and are relatively close in magnitude. Furthermore, standard errors associated with the EM regression are substantially lower than the other two methods; this is an expected result of EM estimation. The estimated standard errors are too low because the estimator assumes that complete data exists in all cases (Allison, 2002). Due to the reduced standard errors, all parameter estimates are significant at the 10% level, while most are significant at the 1% level.

Although the parameter estimates from the EM procedure are ML results, the estimated covariance matrix is not. Using a biased estimated covariance matrix could adversely affect policy recommendations. In this study, results from EM estimation may have overemphasized the significance of cross-price terms from the variable input portfolio, which might favor implementation of indiscriminate input controls such as time-area closures.

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